MASTER COPY KEEP FOR REPRODUCTION PURPOSES

REPORT DOCUMENTATION PAGE	Form Approved OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE October 1997	3. REPORT TYPE AND DATES COVERED Technical Report

4. TITLE AND SUBTITLE
Recording and Playback of Collaborative Desktops on the Internet

5. FUNDING NUMBERS
DAAH04-94-G-0280

6. AUTHOR(S)
A. Khetawat, H. Lavana, F. Brglez

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)
Collaborative Benchmarking Laboratory
Department of Computer Science
North Carolina State University
Box 7550 NCSU
Raleigh, NC 27695-7550

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army Research Office
P.O. Box 12211
Research Triangle Park,, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
ARO 33616.5-EL

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

19980521 126

13. ABSTRACT (Maximum 200 words)

This paper presents a Tcl/Tk recording/playback architecture and implementation that records, plays back and executes a Tcl/Tk collaborative Internet-based desktop. Specifically, the desktop brings together distributed data, application workflows, and teams into collaborative sessions in which the control of the desktop editing and execution is shared. A typical workflow invokes distributed tools and data to support the design of microelectronic systems.

We argue that recording and playback of collaborative user interactions can have a wide-range of applications, such as: `keeping minutes' of interactive discussions, clicks of menu-specific commands associated with different tools on the shared desktop, user-entered data and control inputs, user-queried data outputs, support for automated software documentation, tutorials, collaborative playback of tutorials and solutions recorded earlier, etc.

The summary of 540 Internet-based experiments, each relying on RecordTaker and PlaybackMaker to record, playback, and execute ReubenDesktop configurations from local, cross-state, and cross-country servers, demonstrates the effectiveness of the proposed concepts and implementation.

14. SUBJECT TERMS
recording, playback, desktop, collaborative, workflow, Internet

15. NUMBER IF PAGES
7

16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
298-102

CBL (Collaborative Benchmarking Laboratory)
Department of Computer Science
Campus Box 7550
North Carolina State University
Raleigh, NC 27695

Recording and Playback of Collaborative Desktops on the Internet

Amit Khetawat Hemang Lavana Franc Brglez

Technical Report 1997-TR@CBL-06-Khetawat
October 1997

If you choose to cite this report, please add the following entry to your bibliography database:

```
@techreport{
1997-TR@CBL-06-Khetawat,
author = "A. Khetawat and H. Lavana and F. Brglez",
title  = "{Recording and Playback of
Collaborative Desktops on the Internet}",
institution = "{CBL, CS Dept., NCSU, Box 7550, Raleigh, NC 27695}",
number = "1997-TR@CBL-06-Khetawat",
month  = "Oct",
year   = "1997",
note   = "{Also available at http://www.cbl.ncsu.edu/publications}"
}
```

To contact the Collaborative Benchmarking Laboratory via Internet, you may consider:

WWW :	http://www.cbl.ncsu.edu/
Anonymous FTP :	ftp://ftp.cbl.ncsu.edu
For an auto-reply:	benchmarks@cbl.ncsu.edu
To deposit a file at CBL:	ftp cbl.ncsu.edu cd /pub/Incoming put new_benchmark.tar.Z

Technical Report 1997-TR@CBL-06-Khetawat (October 1997)

Recording and Playback of Collaborative Desktops on the Internet

Amit Khetawat Hemang Lavana Franc Brglez
CBL (Collaborative Benchmarking Laboratory)
Department of Computer Science
Box 7550, NC State University,
Raleigh, NC 27695, USA
http://www.cbl.ncsu.edu/

Abstract – *This paper presents a Tcl/Tk recording/playback architecture and implementation that records, plays back and executes a Tcl/Tk collaborative Internet-based desktop. Specifically, the desktop brings together distributed data, application workflows, and teams into collaborative sessions in which the control of the desktop editing and execution is shared. A typical workflow invokes distributed tools and data to support the design of microelectronic systems.*

We argue that recording and playback of collaborative user interactions can have a wide-range of applications, such as: 'keeping minutes' of interactive discussions, clicks of menu-specific commands associated with different tools on the shared desktop, user-entered data and control inputs, user-queried data outputs, support for automated software documentation, tutorials, collaborative playback of tutorials and solutions recorded earlier, etc.

The summary of 540 Internet-based experiments, each relying on RecordTaker *and* PlaybackMaker *to record, playback, and execute* ReubenDesktop *configurations from local, cross-state, and cross-country servers, demonstrates the effectiveness of the proposed concepts and implementation.*

Keywords: recording, playback, desktop, collaborative, workflow, Internet.

I. Introduction

The Internet and the on-going evolution of the world-wide web is expected to evolve into a network without technologic, geographic or time barriers – a network over which partners, customers and employees can collaborate at any time, from anywhere, with anyone. Even before the emergence of the Internet, the design of microelectronic systems increasingly relied on globally distributed databases, tools, and design teams. The challenge of the Internet is how to make this process more user-friendly, efficient, and effective – at a cost that is transparent to end-users.

Customization, coordination, and repeated execution of a collaborative Internet-based desktop environment for a specific design project is a non-trivial task, especially for a complex project involving a large number of distributed data, tools, and team members. To support such efforts, we have developed two utilities: *RecordTaker* and *PlaybackMaker*. Since this work started before the advent of JAVA [1], the current prototypes are written in Tcl/Tk [2]. Both can record, playback, and execute the collaborative Internet-based *ReubenDesktop* environment described in [3, 4]. We argue that recording and playback of collaborative user interactions can be seen as 'keeping minutes', not only of the interactive discussions but also of the menu-specific commands associated with different tools on the shared desktop, of user-entered data inputs, and of user-queried data outputs. There are other benefits of recording, such as

(1) support for automated software documentation and tutorials, capturing the dynamics of software interactions for playback and review at a later time;

(2) study of activities and feedback on how teams actually collaborate, to improve the effectiveness and efficiency of collaborative environments;

(3) remote assistance, by selecting and playing back effective solutions recorded earlier.

Today, the basic desktop environment of a computer display is largely determined by the windowing/operating system of the host, e.g. MacOS and WindowsNT. The Common Desktop Environment (CDE) that makes applications running on UNIX systems portable and easy to use is a relatively recent commercial development [5]. Alternatively, there is TkDesk [6], a public-domain desktop and file manager for Unix and X written in Tcl/Tk. Prototypes of environments that provide user-configurable GUI capabilities for *collaborative* Internet-based desktop computing, with data and applications distributed on different hosts, have been demonstrated only recently [3, 4, 7, 8][1].

Much of the research on issues addressed in this paper predates the challenges and opportunities that have arisen with the Internet. For example, an overview of research issues related to sharing applications is presented in [9, 10, 11]. Some of the existing systems which provide a recording mechanism include [12, 13, 14, 15]. In most of the systems listed above, the implementation has been done using X protocols [16, 17]. A notable exception is the *TkReplay* [12], which provides an extension to Tcl/Tk.

The paper is organized into the following sections: (2) background and motivation, to define a collaborative environment and illustrate collaborative remote assistance using playback; (3) recording and playback architecture; (4) recording and playback implementation; (5) summary of 540 Internet-based experiments, and (6) conclusions.

II. Background and Motivation

The *ReubenDesktop*, described in this paper as recordable and executable upon playback, satisfies the following properties as a collaborative desktop environment [4, 7]:

- **P1:** desktop is shared and multi-cast, so that each participant can observe desktop actions of the others;
- **P2:** desktop supports a shared and segmented 'talk window', so each participant can type messages to all others in his/her own window segment;

This research was supported by contracts from the Semiconductor Research Corporation (94-DJ-553), SEMATECH (94-DJ-800), and DARPA/ARO (P-3316-EL/DAAH04-94-G-2080).

[1] See also EE-Times report (16 June 1997) on DAC'97 demos, under URL http://www.techweb.com/se/directlink.cgi?EET19970616S0001

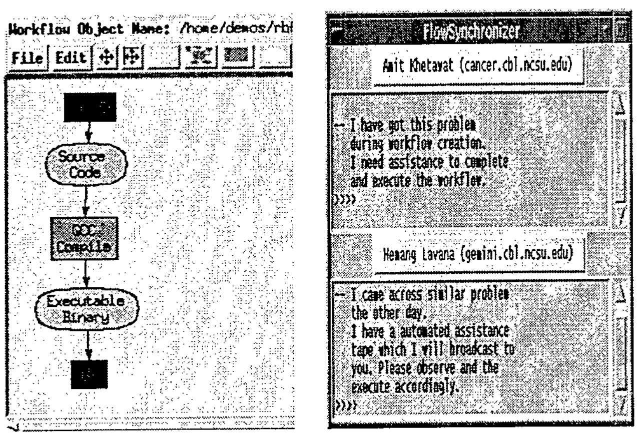
P3: the shared and segmented 'talk window' supports a token passing mechanism, so that at any time, only *a single user* controls the desktop, but can pass the token to any other user when requested.

An example of a *ReubenDesktop* satisfying properties **P1–P3** is shown in Figure 1(a). The instance of the particular desktop has been multi-cast by student Amit to his instructor Hemang with a request for on-line assistance. In the case shown, the desktop consists of two windows: (1) a sample workflow that is not executing, hence the problem, and (2) a *FlowSynchronizer* window that allows Amit and Hemang to 'talk' and describe the problem and a solution.

Here, instructor Hemang could have requested and received permission from Amit to edit the workflow and thus show a solution. Instead, Hemang remembers that earlier, he *recorded* a solution to a similar problem for another student. Subsequently, he decides to *playback* the pre-recorded solution, shown in Figure 1(b). By passing control to Amit (the respective *FlowSynchronizer* window is not shown), Amit can now study the solution by re-executing the *PlaybackMaker*.

It is clear that the paradigm described in this example applies to a number of situations, including design reviews, with high potential to reduce design errors or catch them early in the process, thereby significantly enhancing the productivity of the team effort.

(a) Collaborative description of a problem



(b) Collaborative playback of a tutorial workflow

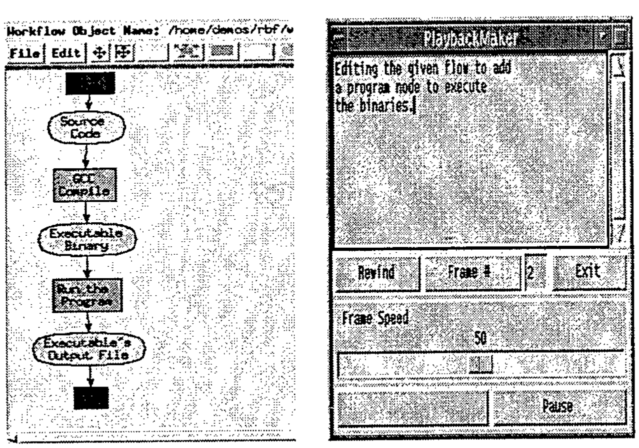


Fig. 1. Collaborative remote assistance using playback.

III. Architecture

Recording and playback essentially involves capturing all events that are generated during a session, and reproducing those events in exactly the same sequence as they were generated. *Event* is an occurrence of an interaction between the user and the windowing system. The windowing system constitutes the local display, the keyboard, and the mouse.

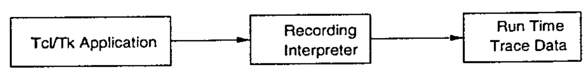
In order to distinguish between the events occurring during recording and playback, we categorize the events into two types:

Window events are generated by the windowing system during *run time* of an application, in response to the interaction of the user with the application.

Synthesized events are invoked internally by the application using Tcl/Tk commands and not in response to user input. The Tcl/Tk interpreter arranges for the synthesized event to be processed just as if it were a part of the user input from the window system.

Every event consists of at least one primitive component. It may also contain additional secondary components for details. Examples of primitive components, which occur when the user interacts with an application on the local windowing system include: *ButtonPress, ButtonRelease, MouseMotion, KeyPress.* The secondary component associated with each event describes details such as the x-y coordinates of the mouse on the screen, the key which was pressed, the mouse button number which was clicked, etc.

(a) Block diagram of recording session



(b) Block diagram of playback session

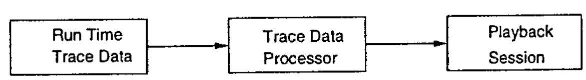


Fig. 2. Recording and playback architectures.

Recording Session Architecture. Figure 2(a) shows the block diagram for the recording session. During the recording mode, the Tcl/Tk code passes through a *Recording Interpreter* which records the user interactions with the application and generates the *Run Time Trace Data.* The recording session also provides a facility to segment the entire playback session into several frames. The user can also insert a description about each frame which will be replayed during the playback session.

Recording Interpreter Implementation. Tcl/Tk applications have an event-driven control flow, just as with most window system toolkits. An event is handled by associating a Tcl/Tk command to the event with the `bind` command. Each Tk widget has default bindings for some of the events which provides the basic functionality of that event with the widget, e.g. the event *Enter* inside a *button* widget highlights the button. Event bindings are structured into a simple hierarchy of global bindings, class bindings, and instance bindings. Tcl/Tk provides the default behavior of buttons as bindings on the *Button* class.

We introduce a new class called *RecordClass,* create new bindings for each event we want to record, and associate these bindings with the RecordClass. This RecordClass is attached to each widget of the application to be recorded. The attachment is done when the widget is created on the screen by using the `bindtags` command.

The Trace Data Structure, used to store the information

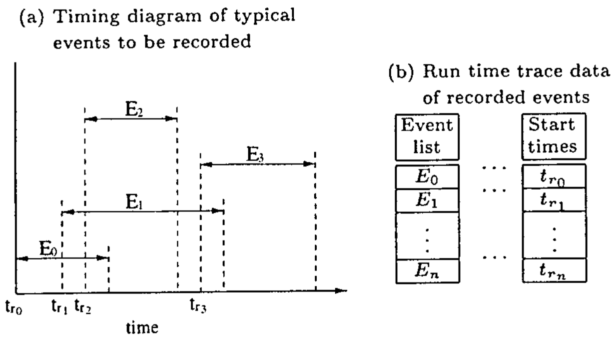


Fig. 3. Details of event timings during recording mode.

about the intercepted events, is implemented using Tcl/Tk's associative arrays. This data format makes it easier to analyze and create commands which would replay those events.

We also store the timings for each event. Timing information associated with each event is very critical, and is useful for synchronizing the synthesized event during the playback session. Various terms related to a recording session are as follows:

- E_i — The i^{th} event in a session.
- t_{r_i} — The time at which event E_i occurs during a recording session.
- $t_{r_{i+1}} - t_{r_i}$ — The time difference between the occurrence of the event E_{i+1} and the event E_i.
- n — The total number of events for a session.

Figure 3(a) shows a timing diagram illustrating the relationship between various events and their recording times. Figure 3(b) shows a part of the trace data, which is a list of events and their corresponding recoding times.

Playback Session Architecture. Figure 2(b) shows the block diagram for the playback session. During the playback mode, the Trace Data Processor reads the trace data and creates commands to synthesize the recorded events. These synthesized events are then scheduled by using event timings to create the playback session. The playback session can be controlled and tailored at the user's convenience.

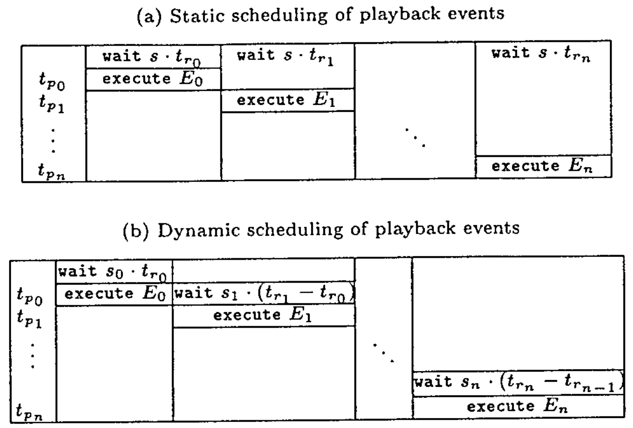
Trace Data Processor Implementation. Tcl/Tk provides a command `event generate` to synthesize the recorded window events. The Trace Data Processor creates the synthesis commands for each of the recorded events with every detail about that particular event. The `event generate` command has the following format:

```
event generate window event [options]
```

The *window* is the widget in which the *event* is to be synthesized. The options are used to specify the details which are specific to each particular event. In addition to the basic event synthesis command, Trace Data Processor also creates the dynamic timing information for that event. This dynamic timing event allows the user to playback in a user-friendly manner. Some of the terminologies related to the playback session are as follows:

- t_{p_i} — The time at which event E_i will be played back.
- s — Constant scale factor. This scaling factor remains constant for the entire playback session of all n events and is pre-computed at the start of a playback session.
- s_i — The dynamic scaling factor for the i^{th} event. This scaling factor may change anytime during the playback session.

The two schemes we considered to implement the timing details are given in Figure 4. Both the schemes use the `after` command provided by Tcl/Tk to schedule an event at a later time. Figure 4(a) shows the static scheduling of events in which all the n events are scheduled at the start of a playback



(c) Comparision of static and dynamic scheduling of playback events

Playback time	Static scheduling	Dynamic scheduling
t_{p_0}	$s \cdot t_{r_0}$	$s_0 \cdot t_{r_0}$
t_{p_1}	$s \cdot t_{r_1}$	$t_{p_0} + s_1 \cdot (t_{r_1} - t_{r_0})$
t_{p_2}	$s \cdot t_{r_2}$	$t_{p_1} + s_2 \cdot (t_{r_2} - t_{r_1})$
$\vdots$	$\vdots$	$\vdots$
t_{p_n}	$s \cdot t_{r_3}$	$t_{p_{n-1}} + s_n \cdot (t_{r_n} - t_{r_{n-1}})$

Fig. 4. Scheduling recorded and playback events.

session. The time, for which the event E_i is scheduled to execute, is computed by multiplying t_{r_i} with the constant scale factor s. This approach has several limitations which include the inability to schedule events dynamically during the playback session. This limits the user's ability to pause or vary execution speed between consecutive events.

This limitation can be overcome by using a dynamic approach, as depicted in Figure 4(b). In this approach, the event E_{i+1} is scheduled at the start of execution of event E_i. The scaling factor used for scheduling event E_{i+1} is computed not at the start of playback session but at the start of execution of event E_i. This gives the user flexibility to pause during playback, or dynamically scale down or scale up the playback speed. A comparison between the approaches is shown in Figure 4(c).

IV. Recording and Playback Tools

We use a simple application `Print Hello` button in Figure 5 to illustrate the main ideas used to implement the recording and playback mechanism.

The left side of the figure shows the trace data, and the right side of the figure shows the Tcl/Tk commands used for synthesis of the recorded events and the user views as each event is synthesized.

We now describe the steps illustrated in the Figure 5 to synthesize the events like Enter, ButtonPress, etc.

Step 1. Invoke the button application with the command `pack [button .b -text "Print Hello"]`

Step 2. Synthesize the event 'Enter' in the window '.b' with the command `event generate .b <Enter>`

Step 3. Synthesize the event 'ButtonPress' in the window '.b' with the command `event generate .b <ButtonPress> -button 1`

The option '-button 1' specifies the Mouse button 1.

Recording and Playback Tools. We have implemented a *RecordTaker* and a *PlaybackMaker*. These tools assist users to

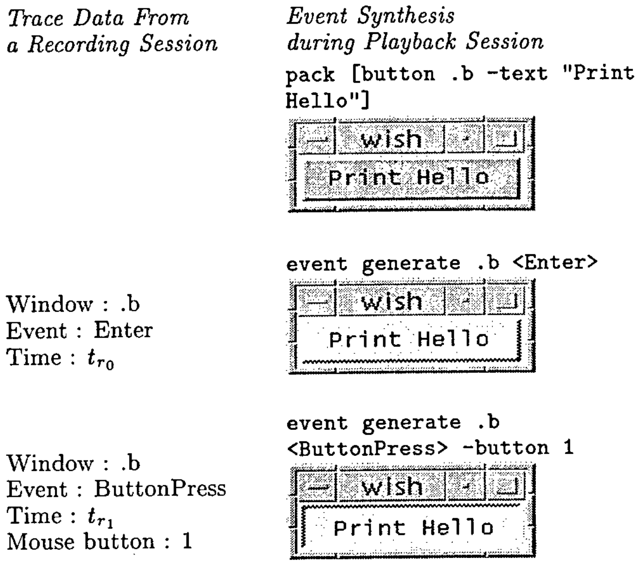


Fig. 5. Details of a recording and playback session.

create customized recordings and to provide convenient playback as described below. Figure 6 shows the GUI of *RecordTaker*, which allows the users to customize their recordings. The *RecordTaker* provides a facility to record a session in a number of steps. It also facilitates the addition of descriptions to each step. These descriptions may be needed to explain the sequence of events during the playback. We introduce the concept of *frames* in this context. Each step is called a frame. The *frame* is essentially a breakpoint, which is inserted while recording a session. Thus a session may be broken up into several frames or it could be a single frame. Each frame itself constitutes several events. The *RecordTaker* interface consists of the following components:

File. This is a menu button, which allows the user to save the recordings, import a particular frame description file, and exit the recording mode.

Next Frame. This button inserts a marker for the current frame. The marker indicates the end of the current frame and the beginning of a new frame. This marker is used during playback session to automatically pause after the set of events in that frame have been played back, and wait for the user to continue.

Current Frame. This is a text label to indicate to the user the frame number of the current frame. The frame number increases as each frame is recorded.

Edit Frame. This button allows the user to go back and edit the description for a particular frame.

Frame #. This is the number of the frame whose description is to be edited.

FrameDescription. This is a text box in which the description of the steps involved in creating a frame, can be recorded.

Figure 1(b) shows the GUI of *PlaybackMaker*, which allows the user to playback a recorded session at his convenience. The *PlaybackMaker* allows the user to control the speed of the playback sessions. The default playback speed is the speed at which the recording was created. It also provides a facility to pause between the playback of two consecutive frames. The *PlaybackMaker* interface consists of the following components:

FrameDescription. This is a text box in which the description of the steps involved in creating a frame appears.

Rewind. This button restarts the playback session.

Frame #. This button displays the number of the current frame being played.

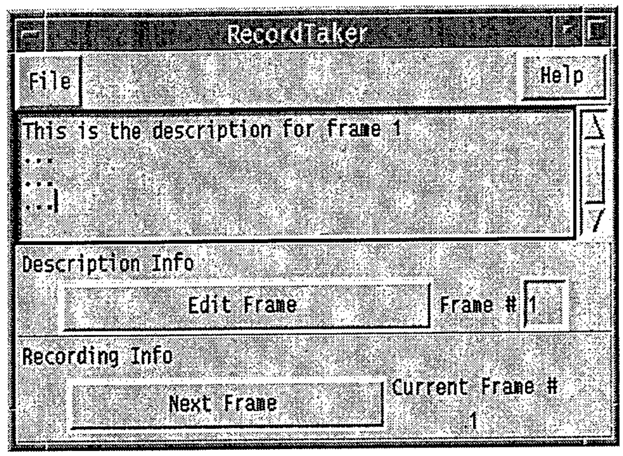


Fig. 6. *RecordTaker*.

Exit. This button exits the playback session.

FrameSpeed. This slider is used to vary the playback speed *within a frame.* This slider provides granularity of scheduling events within a single frame.

Pause. This button pauses the execution of the active frame. It puts a marker on the next step within the active frame.

Continue. This button continues the execution of the active frame from the next step, which had been marked by the Pause button.

V. Experiments

The prototype of an environment that records, plays back and executes a Tcl/Tk collaborative Internet-based desktop, will be put to the test as an integral part of a national-level collaborative and distributed design project involving teams at 8 sites (http://www.cbl.ncsu.edu/vela/). Specifically, the desktop brings together distributed data, application workflows, and teams into collaborative sessions that share the control of the desktop editing and execution. A typical workflow, such as the one shown in Figure 7, invokes distributed tools and data to support a major phase in the design of microelectronic systems. A detailed description is available in [3, 4].

We argue that recording and playback of collaborative user interactions can have a wide-range of applications, such as: 'keeping minutes' of interactive discussions, clicks of menu-specific commands associated with different tools on the shared desktop, user-entered data and control inputs, user-queried data outputs, support for automated software documentation, tutorials, collaborative playback of tutorials and solutions recorded earlier, etc. The 540 experiments, summarized in this section, are the initial part of the Internet desktop environment performance and functionality evaluation, conducted before its release to Vela Project participants and others.

Each of these experiments relies on *interactive* user inputs. To maintain consistency of user inputs during the repeated trial executions across the Internet (with variable quality-of-service), we first *record* a single reference instance of each test case on the local server (without relying on the network) and then move these recordings to cross-state and cross-country servers on the Internet. Each server has an executable version of *ReubenDesktop*, *OmniBrowser*, *RecordTaker*, and *PlaybackMaker*. The experiments are initiated with a *playback* that executes recorded instances of test cases, multi-casting them to 1, 2, or 3 workstation displays at CBL. Additional details

TABLE I

SUMMARY OF 540 EXPERIMENTS PERFORMED ON THE INTERNET AMONG THREE SITES.

Operation	Reference Server	CBL Server						Duke Server						UCB Server					
		1-client		2-clients		3-clients		1-client		2-clients		3-clients		1-client		2-clients		3-clients	
Real Time[a]	Rec	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
CPU Time[b]		Usr	Sys	Usr	Sys	Usr	Sys	Usr	Sys	Usr	Sys	Usr	Sys	Usr	Sys	Usr	Sys	Usr	Sys
Co-editing-1	119.4	122.4	125.2	127.9	130.1	132.5	135.3	118.7	119.9	130.3	132.2	138.8	141.5	127.8	128.8	147.7	149.0	160.5	161.8
		4.0	1.0	21.2	0.9	26.0	1.0	2.2	0.7	11.9	0.5	14.3	0.8	3.9	1.2	20.5	1.1	25.2	1.5
Co-editing-2	153.1	157.8	168.3	163.5	165.0	169.7	172.2	151.9	153.6	167.2	178.7	178.7	181.0	162.5	162.9	185.8	187.0	202.2	209.6
		5.2	1.0	31.1	1.1	38.4	1.3	5.5	1.3	18.7	0.6	22.2	0.8	5.2	1.4	30.0	1.4	37.4	1.8
Co-editing-3	223.8	248.1	258.4	255.2	257.1	265.5	267.9	232.8	236.2	257.0	267.2	273.3	277.0	246.9	247.8	281.5	283.1	310.6	317.0
		14.3	1.2	57.3	1.5	66.8	1.7	8.4	1.2	30.4	1.2	36.0	1.5	14.3	1.8	53.4	2.1	64.8	2.2
Co-browsing-1	136.7	131.2	134.5	131.3	144.2	151.3	160.0	128.8	129.9	138.3	141.0	142.5	152.4	140.0	151.1	155.4	231.8	217.2	233.9
		6.2	1.2	45.1	1.9	62.5	2.9	3.5	0.8	23.1	1.1	29.7	1.3	6.3	1.6	40.7	2.0	53.9	2.6
Co-browsing-2	159.2	158.6	167.2	157.9	172.4	223.5	284.3	155.3	156.7	161.6	164.1	168.3	170.7	167.3	170.4	183.0	191.6	240.9	282.0
		28.5	2.0	80.6	4.1	104.9	7.9	6.5	0.9	32.7	1.4	42.7	1.7	28.6	1.9	78.7	3.8	100.3	4.9
Co-execution-1	305.6	337.7	357.8	357.6	374.1	367.0	392.7	326.4	328.2	340.2	344.5	349.3	352.3	353.1	356.1	368.6	395.5	391.3	422.1
		20.4	4.4	84.1	4.8	104.4	5.5	5.5	1.3	18.7	0.6	22.2	0.8	19.8	4.0	73.4	5.5	96.1	4.8

[a] Both minimum and maximum values of 'real_time' are reported.

[b] Only average values of 'user_time' and 'system_time' are reported.

about these tools are available in [3, 7, 8]. Experiments reported in this section support a conjecture that will be the subject of more detailed experimentation later:

> *Task-specific performance of a single/multiple client-server* ReubenDesktop *execution can be predicted, under comparable server and network loading, by measuring the performance of pre-recorded task-specific experiments that are executed and multi-cast by the server to one/multiple client displays.*

In other words, to assess the performance of *interactive distributed sessions that involve one or more participants*, we have verified that the experiments, as reported in this section, can be extrapolated by measuring the performance of single- and multi-cast executions that are based on playback of pre-recorded experiments on a reference server. The benefits of not requiring a number of individuals to sit through repeated session experiments are obvious. Specifics about the testbed configurations, test cases considered, and tabulated results follow.

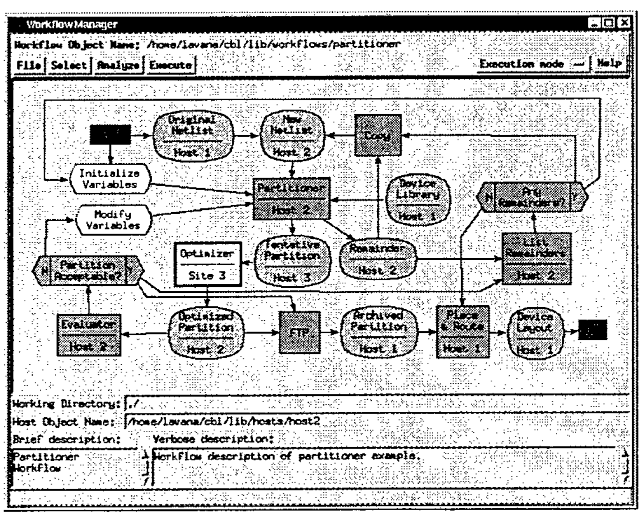


Fig. 7. Partitioner workflow.

Testbed Configurations. In order to approximate typical instances of a distributed multi-site collaborative desktop environment, we have created:

(1) local environment by installing the desktop software on a CBL server[2] which is multi-casting its desktop to one or more CBL client hosts;

(2) cross-state environment by installing the desktop software on a server[3] at Duke University in Durham, NC, which is multi-casting its desktop to one or more CBL client hosts; and

(3) cross-country environment by installing the desktop software on a server[4] at the University of California in Berkeley, CA, which is multi-casting its desktop to one or more CBL client hosts.

Test Cases. We have created and *recorded*, directly on the CBL server under negligible loading conditions, six test cases of collaborative sessions with useful attributes that demonstrate typical user-invoked tasks. The brief description that follows includes the reports of *real_time, user_time* and *system_time* as produced by the Unix utility `time`. The 'real_time' corresponds to the 'stopwatch_time' that could have been obtained by the user monitoring the task. The 'user_time' is the time required by the CPU to complete the task. The 'system_time' is the CPU time required by the system on behalf of the task. A brief description of all test cases engaging two participants, that were recorded for the experiment, follows.

(1) Co-editing-1 (real_time=119.4s, user_time=31.1s, system_time=1.5s): Using *ReubenDesktop*, we *open, and edit*, a simple 4-node, 3-arc workflow by selecting, opening, and closing a single data file node-configuration window.

(2) Co-editing-2 (real_time=153.1s, user_time=44.0s, system_time=1.9s): Using *ReubenDesktop*, we *open, and edit*, the same 4-node, 3-arc workflow by selecting, opening, and closing a single data file node-configuration window and a single program node-configuration window.

(3) Co-editing-3 (real_time=223.8s, user_time=67.5s, system_time=2.5s): Using *ReubenDesktop*, we *open, and edit*, the 17 node, 22 arc workflow by selecting, opening, and closing 3 data files and a single program node-configuration windows.

(4) Co-browsing-1 (real_time=136.7s, user_time=56.1s, system_time=2.1s): Using *OmniBrowser*, we *traverse* a directory structure, located on the server's local file system, across 3-levels, with up to 141 items in each directory. The directory structures of all the three servers were made exactly the same for uniform comparison.

(5) Co-browsing-2 (real_time=159.2s, user_time=97.5s, system_time=5.0s): Using *OmniBrowser*, we *select, open, and scroll*, from start to end, the same copy of a text file of about 1000 pages (2.2Mb), located on each server.

[2] SUN SPARC 20 (chip=60MHz memory=64Mb swap=732Mb)

[3] SUN SPARC Ultra 1 (chip=167MHz memory=256Mb swap=288Mb)

[4] SUN SPARC 20 (chip=60MHz memory=96Mb swap=365Mb)

(6) Co-execution-1 (real_time=123.9s, user_time=90.0s, system_time=3.8s): Using *ReubenDesktop*, we *open, and execute*, the hierarchical workflow in Figure 7. As shown, the workflow has 22 nodes and 28 arcs; during execution, the node labeled as `optimizer` expands into a sub-workflow with 14 nodes and 15 arcs.

All test cases involved two participants working collaboratively and consisted of exchanges of several dialogs via the *FlowSynchronizer* between the two, during each recording session.

Evaluation Method. All software and the files of six test cases, recorded directly on the CBL server, have been replicated on the server at Duke U. and the server at UCB. Scripts have been invoked, *during the night when both servers and the network were least loaded,* to execute the 540 experiments as follows:

```
From each of the three servers, execute and
multi-cast 10-times, with interval of 30 seconds
between each execution:
```

(1) successively to one, two, and three client hosts at CBL, recordings of *co-editing-1, co-editing-2, co-editing-3*;

(2) successively to one, two, and three client hosts at CBL, recordings of *co-browsing-1, co-browsing-2*;

(3) successively to one, two, and three client hosts at CBL, recording of *co-execution-1.*

A log file, generated by `time` (real_time, user_time, system_time) command, archives timing data for each experiment. Similarly, a log file, generated by `sar` (system activity report) command, archives the load on each of the three servers during the execution of these experiments. The log file generated by `sar` provided the information whether or not both the load on the server and the network was sufficiently stable to accept the 'real_time' and 'user_time' results for tabulation.

Table I summarizes results of these experiments as follows:

(1) The first column lists all the six test cases.

(2) The second column reports the time required to record the example on the reference server.

(3) Each cell in the remaining columns contains four values. The top two entries report the minimum and maximum values of 'real_time' and the bottom two entries report the average values of 'user_time' and 'system_time' for each experiment.

Summary of Results. The data presented in Table IV allows us to evaluate the performance of Internet-based desktop environments.

1. The 'real_time' for playback to a single-client on the reference server is approximately the same as the time required to record the test cases.
2. The 'real_time' for playback from other servers varies, depending on the distance between the host server and its clients and the characteristics of the host server. Specifically, for single-client playback, Duke server consistently reported least execution times, followed by CBL server and UCB server. This is attributed to the higher performance server at Duke. However, for multi-clients, the execution times increased with distance in the order CBL, Duke, and UCB.
3. When the experiment is multi-cast to 2-clients or 3-clients, it takes slightly more time, of the order of few seconds, for execution than the time required for single client execution. The negligible increase in the playback time for multi-client execution is due to the fact that the exchange of dialog among participants is computationally least intensive.
4. The variations in minimum and maximum values of 'real_time' for each experiment are negligible since the experiments were performed during the night. However, the same experiments showed significant variations during the day when the network traffic and the server load is unpredictable.
5. Comparing the 'user_time' and the 'system_time' for each server, we find that the CBL server requires the most CPU time and the Duke server requires the least CPU time. This follows directly from the different types of processors and the configuration of each server.

Observations. The successful completion of all 540 experiments provides us with assurance that the experiments are consistently reproducible on a variety of servers, given that the server nominal load is small and that the network is stable. Specifically, we confirmed that

- Repeated *real time* executions of experiments, where user-inputs are carefully and consistently entered (rather than pre-recorded), gives 'real_time', 'user_time', and 'system_time' performance that is comparable (within 10%) of the times reported for pre-recorded execution on any server – provided that the server load and network conditions are as favorable.
- The performance of the Internet-based desktop environment, even in a *collaborative mode*, is quite good under nominal network traffic and load on the server. Hence, with sufficient network bandwidth and powerful processors, it is possible to work collaboratively with efficiency and effectiveness even when participants are dispersed across the continent.
- As the number of clients, corresponding to each participant, increase from 1 to n during playback, the increase in 'real_time' execution is of the order of few seconds only. Again, this increase is subject to the server and network performance and the amount of dialog among participants present in the recording.

Conclusions

We have proposed a Tcl/Tk recording/playback architecture and an implementation that records, plays back and executes a Tcl/Tk collaborative Internet-based desktop. Both tools, *RecordTaker* and *PlaybackMaker*, can be used as stand-alone Tcl/Tk applications or as a part of a larger system such as *ReubenDesktop.*

We envision that a number of collaborative user interactions and Internet users will find useful application of the proposed recording and playback mechanisms. Specifically, considerable resources would be required to conduct the feasibility of collaborative remote user-interactions, sharing of tools, and desktops to accumulate as much information as we tabulated on the 540 Internet-based experiments in this paper. Without the *RecordTaker* and *PlaybackMaker*, we would require a number of participants over an extended period of time.

There are a number of new features that will will extend the applications and the utility of *RecordTaker* and *PlaybackMaker.* These include:

(1) an environment in which several recordings can be spliced together to create a new recording.

(2) extending the recording and playback collaborative environment to the World Wide Web (WWW). Such an environment can be seen as a new service, available from the WWW.

Acknowledgments. We could not have reported as comprehensively on the results of our Internet Desktop experiments without getting generous user accounts on two remote servers, facilitated by Dr. Richard Newton at UC Berkeley and Dr. Gershon Kedem at Duke U. We thank them and their support staff for this privilege.

REFERENCES

[1] The Java Home Page. Published under URL: http://java.sun.com/, 1997.

[2] The Tcl/Tk Project At Sun Microsystems Laboratories. Published under URL: http://www.sunlabs.com:80/research/tcl/, 1997.

[3] H. Lavana, A. Khetawat, F. Brglez, and K. Kozminski. Executable Workflows: A Paradigm for Collaborative Design on the Internet. In *Proceedings of the 34th Design Automation Conference*, pages 553–558, June 1997. Also available at http://www.cbl.ncsu.edu/publications/.

[4] H. Lavana, A. Khetawat, and F. Brglez. Internet-based Workflows: A Paradigm for Dynamically Reconfigurable Desktop Environments. In *ACM Proceedings of the International Conference on Supporting Group Work*, number 1997-GROUP-Lavana, Nov 1997. Also available at http://www.cbl.ncsu.edu/publications/.

[5] The Common Desktop Environment Technical Library. Published under URL: http://www.aw.com/devpress/series/cde.html, 1997.

[6] Christian Bolik. Tkdesk. Published under URL: http://sun1.rrzn-user.uni-hannover.de/~zzhibol/tkdesk/, 1997.

[7] Amit Khetawat. Collaborative Computing on the Internet. Master's thesis, Electrical and Computer Engineering, North Carolina State University, Raleigh, N.C., May 1997. Also available at http://www.cbl.ncsu.edu/publications/.

[8] H. Lavana, A. Khetawat, and F. Brglez. REUBEN 1.0 User's Guide. CBL, Research IV, NCSU Centennial Campus, Box 7550, Raleigh, NC 27695, 1997. Also available at http://www.cbl.ncsu.edu/publications/.

[9] P. Sørgaard. A cooperative work perspective on use and development of computer artifacts. In *the 10th Information Systems Research Seminar in Scandinavia, Vaskivesi*, August 1987.

[10] H. Abdel-Wahab and K. Jeffay. Issues, Problems and Solutions in Sharing X Clients on Multiple Displays. In *Journal of Internetworking Research and Experience*, pages 01–15, March 1994.

[11] G. Chung, K. Jeffay and H. Abdel-Wahab. Dynamic Participation in Computer-based Conferencing System. In *Journal of Computer Communications*, pages 07–16, Vol. 17, No. 1, January 1994.

[12] Charles Crowley. TkReplay: Record and Replay in Tk. In *Proceedings of the Tcl/Tk Workshop, Toronto, Canada*, July 1996.

[13] D. Annicchiarico, R. Chesler, and A. Jamison. XTrap Architecture. Digital Equipment Corporation, July 1991.

[14] XRunner 4.0: The Standard in X Window GUI Testing. Published under URL: http://www.merc-int.com/products/XRunner4/index.html, 1996.

[15] QC/Replay. Published under URL: http://www.centerline.com/products/qc_rply.html, 1995.

[16] P. Asente, R. Swick, and J. McCormack. *X Window System Toolkit: A Complete Programmer's Guide and Specification*. Digital Press, 1990.

[17] R. W. Scheifler and J. Gettys. *X Window System: the Complete reference to Xlib, X Protocol, ICCCM, XLFD*. Digital Press, 1992.